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When making dynamical judgments, people can make effective use of only one salient dimension of information present in the event. People do not make dynamical judgments by deriving multidimensional quantities. Thus, the adequacy of dynamical judgments depends on the degree of dimensionality that is both (1) inherent in the physics of the event, and (2) presumed to be present by the observer. Support for this proposal was found in studies of people's dynamical understandings of (1) wheels, (2) volume displacements (Archimedes Principle), (3) the surface orientation of liquids, and (4) collisions. Additional support was found in a review of the "Intuitive Physics" literature. Finally, studies of apparent motion indicate that the basic representation of object motions is not dynamical.

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PERCEPTUAL CONSTRAINTS ON UNDERSTANDING PHYSICAL DYNAMICS

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In our research program, we have developed an account of dynamical event complexity, and in testing its predictions, have examined the common sense understandings that people have for a variety of physical phenomena. In essence, we propose that people make judgments about natural object motions on the basis of heuristics that relate to a single dimension of information. By this account, people encounter difficulties when construing dynamical events that are inherently multidimensional, or which have been incorrectly defined by them as being multidimensional. In addition to this technical report, our research program is reviewed in an, in press, article in Journal of Experimental Psychology: Human Perception and Performance (Proffitt & Gilden, 1989).

Our account of dynamical event complexity begins with a distinction taken from physics. Here, it is noted that the dynamically relevant properties of objects are defined by the motion contexts in which they are found. Many contexts, particle motions, can be dynamically analyzed by treating the object as a particle located at its center-of-mass. Free fall is a good example of a particle motion; an object's shape, orientation, size, and so forth are all irrelevant to its dynamical behavior in free fall (assuming a vacuum). Other contexts, extended body motions, require that the object be treated as a multidimensional entity. The rolling of a wheel is a good example of an extended body motion. A wheel's moment of inertia (mass distribution) affects its rolling behavior, and thus, it cannot be dynamically treated as a particle. It is important to emphasize that this categorization depends not on whether objects are particulate or extended, but rather on the motion context in which they are encountered.

We propose that people base their common sense dynamical judgments on a heuristical analysis of separate dimensions. <u>People do not make dynamical judgments by deriving multidimensional quantities.</u> This proposal predicts that people will generally make accurate dynamical judgments in (1) 1-dimensional (particle motion) contexts, or (2) multidimensional (extended body motion) contexts in which circumstances are such that specific judgments can be accurately based on a single information dimension. People are predicted to make erroneous judgments in (1) 1-dimensional contexts that are misconstrued as being multidimensional, and (2) multidimensional contexts in which multidimensional quantities are the necessary basis for accurate judgments.

The technical report is divided into two parts. In the first we develop our account of dynamical event complexity, and in the second, we present a variety of research findings that support its predictions.

Complexity in Natural Motions

Successful appreciations of natural motions depend on the kind of object that is being viewed and the dynamical context in which the viewing takes place. Psychological theories of common sense understandings of natural dynamics must ultimately refer to classical mechanics, because it is in this field that the dynamics of object motions are articulated. The following treatment of analytical dynamics introduces those notions that provide the basis for assessing human abilities in understanding natural motions.

There are two basic ideas that we want to make explicit in this section. The first is that from a formal point of view, the laws of object motion are independent of both the object and the motion under consideration. All equations of motion are derived from a single minimum principle. The second is that there is a hierarchy of object complexity that is manifested when the symmetries in dynamical systems are analyzed from the point of view of invariances in the equations of motion. This hierarchy is especially interesting because there exists a definite limit to object simplicity, and as will be discussed in later sections of this report, this limit is reflected in human performance: Human competence with dynamical systems approaches adequacy only for those systems in which object simplicity is maximal.

The Formal Unity of Natural Motions

Classical mechanics has an historical primacy in physics due to the availability in perception of relevant information. In the other three major branches of physics, electrodynamics, thermodynamics, and quantum mechanics, the individual motions of the relevant particles are invisible. Mechanics, however, treats the motion of rigid bodies that can be seen. Mechanical systems were the first studied because their objects were the first noticed.

The familiarity that we have with mechanical systems is, however, highly deceptive. There is a coherence among mechanical systems that is revealed only when attention is withdrawn from how these systems appear phenomenally, and an abstract point of view is taken. This point of view begins with the replacement of the three dimensional space of world experience with an appropriate mathematical space that more adequately describes the environment of the mechanical system.

One of the key themes of our research program is that people are relatively competent in making judgments about systems governed by linear momentum conservation, but that they are much poorer in judging systems where angular momentum is relevant. Mathematically, these two systems are isomorphic in that there is a single operation that carries the linear domain into the angular domain. This operation is the cross-product with the position vector. In this way forces are mapped into torques, linear momentum is mapped into angular momentum, and Newton's 3rd Law, F=ma, is mapped into $\tau = \frac{dL}{dt}$. This mapping is in fact the manner in which angular systems are introduced pedagogically. Physics textbooks begin with a discussion of linear momentum systems. Not only are these systems simpler in terms of their mathematics, but as we will argue, people have fairly good intuitions about their behavior. In a subsequent section of such textbooks, the cross-product is introduced and the equations for angular momentum systems are derived. At this point, students are introduced to a set of amazing demonstrations that capitalize on precession and the orthogonality of torque and angular momentum to perceived object motions. The difficulty that students have with these concepts is discussed below. The learning of physics requires that students understand the nature of the isomorphism that relates linear and angular systems, and it is, in fact, this isomorphism to which experienced physicists return when asked to explain the unusual behavior of angular systems. They will simply state that F=ma.

A Duality in Motion Contexts

The unity and elegance that characterize a mathematical description of natural motions is not embraced by common sense understandings. Here we introduce the notion that there is a hierarchy of dynamical event complexity, and that human understanding is most competent with those systems at the bottom of the hierarchy. There are three concepts that are critical in the determination of this complexity hierarchy. The first is that complexity is defined in terms of the motion context in which objects appear - not in terms of the objects themselves. The second idea is that the complexity of a mechanical system is related to the symmetries that it possesses. The systems with the greatest degree of symmetry are the least complex. Finally, there is a special class of mechanical systems in which symmetry is maximal; such systems treat the objects within them as extensionless point particles. In all other mechanical systems there is some aspect of the extension of the object in space that is relevant for its motion. What it means for an object to appear in a motion context, and the sense in which a mechanical system has symmetries is the subject of this section.

A mechanical system is a collection of objects moving under the action of external and internal force fields. The properties of individual objects that are dynamically relevant are determined by the motions that they are executing. In this sense, a mechanical system is a context for the objects within it. This notion is best illustrated by a simple example.

Consider the two following contexts for the motion of a top: (1) Free fall of a top that has been dropped in a gravitational field, and (2) precession of a spinning top that is balanced on a pedestal in a gravitational field. Both are examples of a top falling, but the two motions are quite different, as are the properties of the top that are of dynamical relevance. For example, the shape of the top only matters if a torque is applied to it. The trajectory of the center-of-mass of a spinning top in free fall is identical to that of a nonspinning one. For any object in free fall in a uniform gravitational field, the integrated torque, computed about the center-of-mass, is identically zero. On the other hand, a top that is supported by a pedestal is subject to a gravitational torque about the point of contact. In this situation, spinning is relevant to the top's behavior. A nonspinning top falls down; a spinning top falls sideways - that is, it precesses. Spinning tops have many more dynamically relevant features. The basic point here is that: It is not the object per-se that determines its motion, it is the motion, or alternatively the mechanical system, that characterizes the object. The complexity of objects is a reflection of the complexity of the mechanical systems in which they appear.

The complexity of a dynamical system is determined by the symmetries it possesses. Symmetry in a dynamical system is related to the more familiar notions that we have of figural symmetry, but it is not quite the same thing. Figural symmetries are defined in terms of invariance under a class of transformations that include translation, rotation, and reflection. Figures with a high degree of symmetry will be invariant under several of these transformations. Symmetry in dynamical systems is similarly defined except the object that undergoes the transformation is a mathematical equation (the equations of motion), and the transformation can be quite general. The transformations are generated by changing object attributes, and the result of the transformation is determined by the resulting form of the equations of motion.

An important event, of particular interest to us in this paper, is the motion of a wheel rolling down an inclined plane. We take the opportunity here of presenting the physics of the rolling wheel in order to illustrate the concept of dynamical symmetry. In Figure 1, we illustrate two rim-like wheels. One is perched on an inclined plane; the other is held by a thread that will be cut. These two situations define two mechanical systems. Conservation of energy for these systems is written:

(1) $$\frac{1}{2} Mr^2 + \frac{1}{2} J\omega^2 = Mg(h_0 - h) \text{ : rolling}$$

(2) $$\frac{1}{2} Mr^2 = Mg(h_0 - h) \text{ : free fall}$$

where M is the mass of the wheel, B is its inner radius, A is its outer radius, v is its instantaneous velocity, w is its angular velocity about its center-of-mass (C_m), and where the moment of inertia is written

(3) $$J = \frac{1}{2} M(A^2 + B^2)$$

We suppose here that the wheel rolls without slipping so that its velocity down the ramp can be written v=Aw. Solving for the instantaneous velocity of the wheel as a function of the vertical height yields:

(4) $$v = \left(\frac{2g(h_0 - h)}{3/2 + 1/2\, B^2/A^2} \right)^{1/2} \text{ : rolling}$$

(5) $$v = \left(2g(h_0 - h) \right)^{1/2} \text{ : free fall}$$

Analysis of these equations reveals their symmetries. These two systems are essentially distinguished by observing that, for the rolling wheel, kinetic energy is partitioned into both a translational part and a rotational part, whereas for the falling wheel, all kinetic energy is translational. We have canceled out mass from both of these equations indicating that the mass of the wheel does not influence its motion. This is a symmetry that both systems share. Upon cancellation of the mass term, there is nothing left in the equation for the falling wheel that tells us that a wheel is being described. A falling wheel can be distorted in any manner and it will fall along the same trajectory; free fall is a motion context in which objects are treated as extensionless point particles. The rolling wheel, however, does not possess this symmetry. The ratio B/A is present; it defines how mass is distributed in the rim. Note that any transformation of the rim which leaves the ratio B/A invariant will have no effect on the motion. Thus, the rolling wheel is invariant under an overall size transformation, $A \rightarrow pA$, $B \rightarrow pB$, but it is not invariant under a fattening or thinning transformation, $A \rightarrow pA$, $B \rightarrow B$. The existence of a transformation on the spatial properties of the rolling wheel, for which the equation of motion is not invariant, is crucial; the rolling wheel is not being treated as an extensionless point particle - its extension in space is reflected in its motion.

To summarize, there are two distinct ways in which objects may appear in mechanical systems. The distinction is defined by the symmetries of the mechanical system. If a mechanical system is invariant under all transformations that operate on the three dimensional shape and orientation of the objects in motion, then those objects are being treated by the system as extensionless points. Such objects are referred to as point particles. The point particle is characterized only by its position in space and is the simplest object that can exist in a mechanical system.

All other objects are treated by their systems as being extended. Examples of extended body systems are ones in which the objects are subjected to torques, are floating, or are moving through a resistive medium·

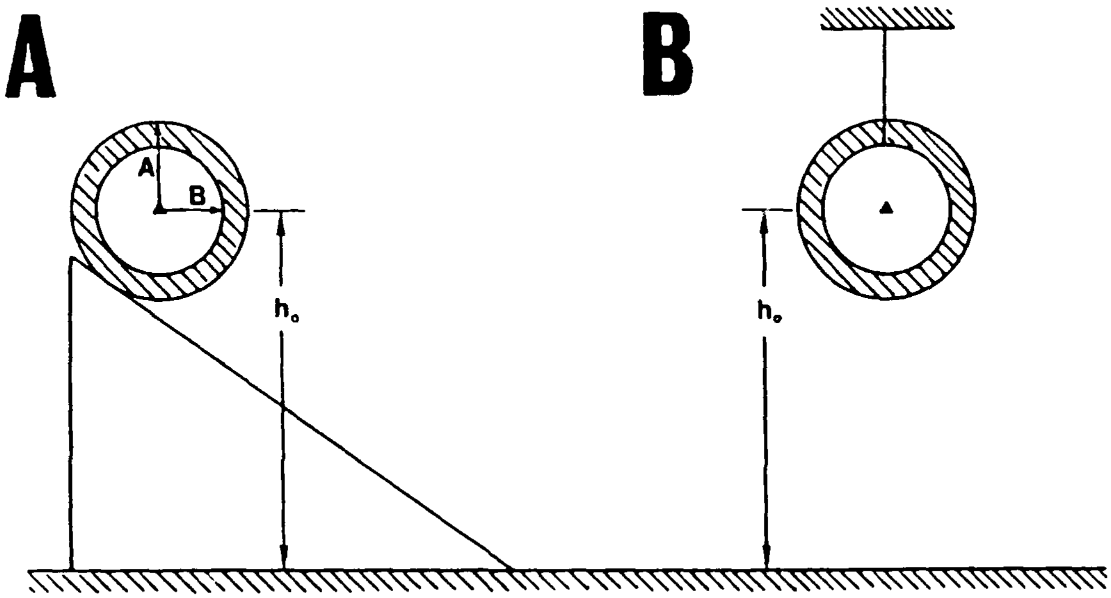

Figure 1: Two Motion Contexts for the Wheel

Extended Bodies and Multidimensionality

The symmetry of a mechanical system is reflected in the amount of information required to represent its dynamics. Those systems in which symmetry is maximal, point particle systems, have exactly one relevant category of information. It is in this sense that particle motions are 1-dimensional and are treated in dynamics as a special case.

The dimensionality of an object in a mechanical system is determined by the number of object attributes that can influence its motion. Point particle systems contain particle position as their single category of information. The very act of looking at the event being displayed is simultaneous with noticing the single dimension required for dynamical analysis of the event.

The vast majority of mechanical systems define extended body motions. Extended body motions are inherently multidimensional in the sense that there is some spatial property of the object, apart from where it is located, which is coupled into its motion. The distinction between point particles and extended bodies is essentially between motion contexts that couple only into particle location and contexts that couple into additional spatial attributes of the body.

The first and most important step in the analysis of multidimensional systems is the formation of *multidimensional quantities*. Such quantities are formed through some sort of multiplication; it does not make sense to add quantities that have different units (dimensions). The kind of multiplication that is appropriate depends on the quantities being combined. For example, torque is formed by the cross product between position and force. Construction of the moment of inertia requires an integration over the mass distribution weighted by the squared distance. Unlike position, such multidimensional quantities are not categories of perception.

Common Sense Understandings of Dynamics

We believe that people do not derive multidimensional quantities when observing natural motions. Thus, we predict that their accuracy in making dynamical judgments will be related to event dimensionality. In particular, we predict that people will exhibit pervasive failures when construing extended body motions.

People's Dynamical Understandings of Extended Body Motions are Relatively Poor.

The following is a summary of our research on people's understandings of a variety of physical phenomena. The common finding of all of this research is that people base their dynamical judgments on one parameter of information that is salient in the event.

Understanding Wheel Dynamics. We conducted a large scale investigation on common sense understandings of the dynamics of rolling wheels and gyroscopes. An example of one of the questions asked in this study was: What influences the rate that a wheel will roll down an inclined plane - its radius, mass, or mass distribution? In fact, the participants of this study were not asked this question directly, but rather were given pairs of wheels that differed on one of these dimensions and asked to predict which member of the pair would roll down the ramp in the least time, or whether both wheels would roll at the same rate. The results of this study showed that people were somewhat unsure, as a group about the influence of radius or mass on a wheel's rolling behavior, but were in greatest agreement that mass distribution (one wheel was a solid disk and the other a rim) was irrelevant. The multidimensional quantity of moment of inertial that describes mass distribution is the only relevant dynamical variable in this situation; however, it was virtually ignored.

This study was repeated with a group of 20 high school physics teachers. It was found that their common sense understandings of angular systems did not differ from the students. Although these teachers could solve the problems analytically if given time and writing materials, when forced to rely on their immediate intuitions, they failed to evidence any benefit from years of instructing others about these simple mechanical systems.

We conducted an assessment of observer's implicit dynamical appreciation of moment of inertia in an ongoing situation that manipulated this variable. We created an animated computer graphics display consisting of a satellite spinning in space. This satellite was constructed solely out of solar panels that could open or close, and thereby, affect the satellite's moment of inertia. (This situation is analogous to a twirling ice skater who extends or contracts her arms.) In a natural situation, the opening of the satellite's solar panels would cause its spinning rate to slow, whereas closing the panels would result in an increased angular velocity. In the animated stimulus displays the opening and closing of the panels resulted in a variety of resulting spin rates. The observer's task for each sequence was to judge whether the resulting angular velocity was the natural outcome of the satellite's changing shape, or whether it could only have been produced by some unseen force.

The results of this experiment were that subjects made only highly qualitative judgments about the influence of changing shape on angular momentum. For the cases in which the satellite's solar panels opened, subjects judged the following outcomes as unnatural without an external force: The satellite stops and reverses its direction of spin, or the satellite simply stops. All other outcomes were judged as being equally natural. In addition to the natural slowing rate, these other outcomes included a situation in which the satellite's angular velocity remained unchanged, one in which it actually sped up, and two in which the spinning rate slowed, but by an incorrect amount. Equivalent results were obtained for the case in which the satellite closes its solar panels. Clearly, these subjects demonstrated only the most rudimentary understanding of the influence of mass distribution on angular momentum.

Studies preformed in conjunction with those on understanding wheel dynamics showed that people have very poor comprehension of gyroscopic motions in at least two respects. First, they do not realize that everyday objects with which they interact behave like gyroscopes. This was found to be the case when people were questioned about the behavior of bicycles. Moreover, even a group of bicycle races that we tested showed little awareness of the gyroscopic properties of their bicycles. Second, when viewing a spinning gyroscope, people exhibit amazement but no comprehension of what prevents the gyroscope from falling over.

These studies are about to be resubmitted to Cognitive Psychology. An earlier submission to this journal was not accepted; however, the editor requested that we resubmit the manuscript after revision.

Understanding Volume Displacements. We conducted a set of experiments on common sense understandings of Archimedes Principle. It was found that people make accurate judgments about volume displacements only when judgments can be based on one object parameter.

Consider the following question adapted from Walker's (1977) book, The flying circus of physics with answers: Suppose that a toy boat is placed into a fish tank, a heavy bolt is put into the boat, and the water level in the tank is marked. If the bolt is removed from the boat and dropped into the fish tank, then what will happen to the height of the water level with respect to the previous mark?

We asked university students many questions related to water displacement. We found that if the questions required the participant to reason about one object parameter at a time, then their performance was nearly perfect and one would surmise that they had a thorough understanding of Archimedes Principle. An example of such a 1-dimensional question is the following: Two objects of different weight are observed floating in identical fish tanks; which object displaces the most water? On the other hand, if they were asked a question, such as the above bolt-in-the-boat question, then their performance fell to a worse than chance level. (In this question the bolt must be construed as a multidimensional entity: Its mass is relevant while it is in the boat; however, its volume becomes its relevant dimension once it is sunken.) Most people erroneously reported that, when the bolt was put into the tank, the water level would remain the same as it had been when it was in the boat. Similar worse than chance performance was found for other questions that required an object to be construed as having more than one dynamically relevant dimension.

We constructed a tank in which the water level could be rapidly raised or lowered by the experimenter at the moment when the bolt was placed into the tank. Subjects were presented with a toy boat floating in the tank and in the boat was a heavy bolt. They were told that the bolt would be taken out of the boat and placed in the tank's water. They were also told that sometimes the water level would be raised or lowered by the experimenter. Their task was to watch pairs of events and determine whether the tank's water level had been influenced by the experimenter. In this ongoing situation, observers reported that the canonical event was natural, and that their own prediction, in which the water rose to its original level after the bolt was placed into the tank, looked highly contrived.

The superior performance that was observed in this ongoing situation, relative to the verbally presented task, is a general finding in many situations that we have investigated. Often, the dimensionality of events are segregated in time when the ongoing event is observed. In the above example, observing the bolt as it is taken out of the boat allows one to see how this heavy object produced a large displacement. Observing the small bolt being placed into the tank, and watching the water level rush back to its initial level, induces considerable mirth since the bolt's size has now become so salient. The dimensions of weight and size are separated in time in the ongoing event but not in the verbally presented question.

These studies formed the bases of a Masters Thesis conducted by Sue Whelan, and we are currently preparing a manuscript for journal submission.

Understanding the Surface Orientation of Liquids. No physical event has been more thoroughly studied in the physics understanding literature than people's common sense notions about liquid surface orientation (Rebelsky, 1964; Thomas, Jamison, & Hummel, 1973; DeLisi, 1983; Kalichman, 1988). When asked to draw, or otherwise indicate the orientation of a liquid's surface that is contained within a tilted container, approximately 35% of the adult population do not draw horizontal lines. Although these people correctly indicate that the orientation inclines toward the lowest lip of the container, they are unsure as to exactly what this relative orientation should be. When asked, many of these people will report that they did not know that liquid surfaces are always horizontal; however, often people who explicitly know the principle make errors, and vice versa (Myer & Hensley, 1984).

Howard (1978) showed contrived animated displays in which a container is tilted back and forth and the contained liquid assumed non-horizontal orientations. He found that these displays did not elicit better performance. As was discussed earlier, we replicated Howard's study, and to our surprise, found that within a certain range of impossibility, these ongoing anomalous events do not look odd.

Later, it occurred to us that liquid surface orientation can be construed as being multidimensional in that there are two psychologically relevant reference frameworks (See Figure 2): (1) The object-relative reference frame is the orientation of the surface relative to its container, and (2) the environmental reference frame is the orientation of the surface relative to the ground. Viewed from the object-relative perspective, the orientation of the liquid's surface is specified by the angle, beta, in the left panel of the figure. Note that without knowing the orientation of the container, there is no precise way of determining what beta should be. Past research indicates that people who get this problem wrong, are as likely to make beta too large as too small, thereby indicating that they are not simply biased toward a local regularization causing them to orient the water level at right angles to the glass (Kalichman, 1988). From an environment-relative perspective, the solution to the problem is trivial - make alpha in the right panel of Figure 2 equal to zero. We suspected that those people who performed poorly on this task did so because they were attempting to solve the problem relative to the irrelevant object-relative reference frame.

To test this possibility, we took photographs of liquids in tilted containers, and also of various other irrelevant scenes. The pictures were cut into circles, mounted onto a vertical turntable, and shown at random orientations to observers. The observers were told to orient each picture so that it appeared upright. For the liquid-in-container pictures, the only cue for upright orientation was surface orientation. We found that people performed almost perfectly at this task; adjustments were typically within a degree of horizontal across subjects, regardless of what they drew on a pretest.

The surface orientation problem can be easily solved if the environmental reference frame is made salient. However, in typical testing situations, subjects often construe this problem as one concerning object-relative orientation. We believe this reflects an experience based perceptual influence. When viewing a cup filled with hot tea, for example, it is important to notice the orientation of the liquid's surface relative to the edges of the cup so as to not spill the drink. Noticing that the surface is horizontal is irrelevant to any practical concern.

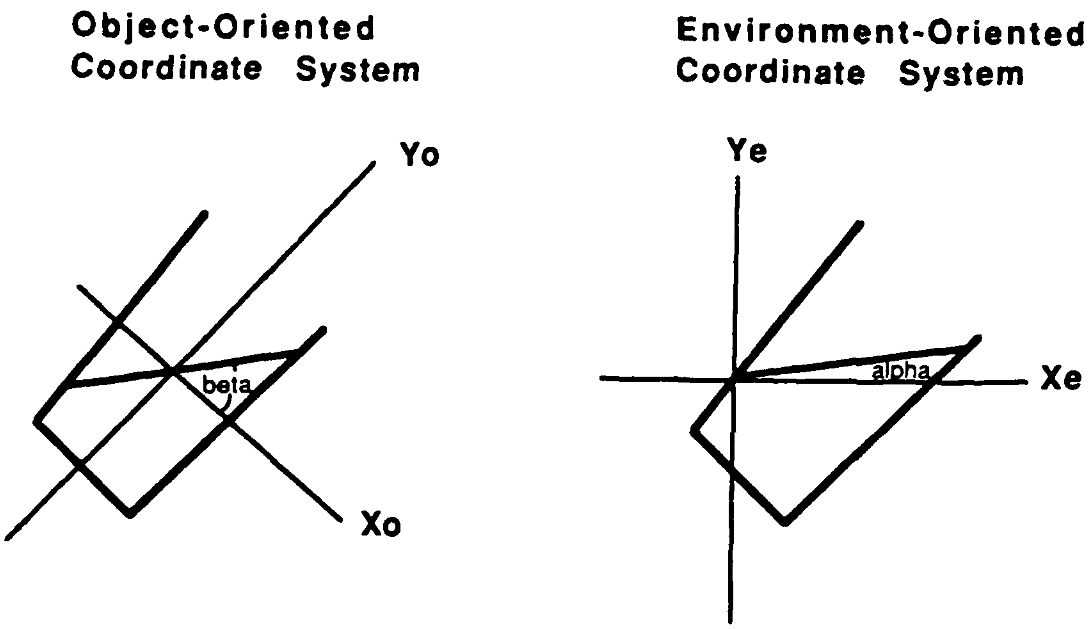

Figure 2: Object- and Environment-relative Coordinate Systems for the Water Level Problem.

Moreover, the task demands of the traditional problem draw attention to the object-relative perspective. Subjects are asked to orient the liquid's surface within a fixed and tilted container. Thomas, Jamison, & Hummel (1973), in fact, used an apparatus that was almost identical to ours. They had their subjects adjust a vertical turntable that oriented a depiction of a liquid's surface behind a fixed, tilted container. Our task differed only in that our procedure required subjects to orient the liquid/container system relative to the environment, as opposed to orienting the liquid relative to its container.

Failure on the water level problem originates in a misrepresentation of the problem, itself. The task presented by Thomas et al. and that presented by us are problem isomorphs (Simon & Hayes, 1976). That is, even though the formal structure of the two problems is identical, the object- or environment-relative representations that subjects give to them may be quite different; these different representations have profound effects on performance. In explicit problem solving, context plays a significant role in defining the relevant aspects of problems (Hayes, Waterman, & Robinson, 1977). Here, we find that the object- or environmental-relative perspective define two contexts in which the problem can be construed. Each context, in turn, specifies the orientation angle, alpha or beta, that is to be derived in solving the problem. When viewed from an environmental perspective, the value of alpha is sought, and is implicitly obvious to almost everyone. When viewed from an object-relative perspective, this implicit knowledge about liquid surface orientation is not evidenced.

This work was the basis of Ellen McAfee's Masters Thesis and was presented this Fall at the Meeting of the Psychonomic Society (Proffitt & McAfee, 1988). It is currently being prepared for journal submission.

Understanding Collision Dynamics. Using the equations of linear momentum conservation, Runeson (1977) showed that when two objects collide, the ratio of their pre- and post-collision velocity differences is equivalent to their relative masses. Runeson (1977) suggested that the sufficiency of kinematic information would allow observers to reliably form judgments of mass ratio on at least an ordinal scale. We tested this hypothesis in a set of experiments on people's ability to judge mass ratios from the motions present in collisions.

In a first experiment, we showed that relative mass can also be derived from post-collision velocity information alone. Observers viewed collisions, sometimes with the pre-collision epoch occluded and sometimes not. It was found that, for those collisions in which people make accurate judgments, occluding the pre-collision epoch does not hinder performance. However, of more interest was the finding that for some collisions, people performed at a chance level. Clearly, the ability to make mass ratio judgments was not a general ability across all collision parameters.

In the second experiment we showed that people based their mass ratio judgments on two heuristics, and do not derive the multidimensional quantity required for general competence. One of these heuristics was related to velocity: After a collision, the faster moving object is lighter. The other heuristic was related to deflection: After a collision, the object that ricochets is lighter. It was found that people based their judgments on the heuristic that was related to the most salient dimension, velocity or deflection angle, present in the event. These heuristics yield good performance for some collision situations, but result in chance performance in others. In particular, there are natural collisions where the ricocheting object recoils at a much slower speed than the object it hit. In these cases the heuristics give conflicting recommendations about which object is lighter. In conflicting situations, the independence and separateness of the heuristics is revealed by the distribution of responses for the estimated magnitude of relative mass. Subjects never "averaged" the ricochet heuristic with the speed heuristic to effect a compromise. That is, no subject ever reported that one ball might be just slightly heavier. Subjects were uniformly impressed that one of the balls was much heavier, although they were divided about which ball that was.

This work is reported in an article that is in press in the Journal of Experimental Psychology: Human Perception and Performance (Gilden & Proffitt, 1989).

People Perform Poorly in Particle Motion Contexts That Are Misconstrued As Being Multidimensional.

In our review article, we reinterpreted much of the literature on people's common sense dynamical understandings (Proffitt & Gilden, 1989). Recently a large number of investigation have been published on these beliefs about dynamics (Champagne, Klopher, & Anderson, 1980; McCloskey, Caramazza, & Green, 1980; Caramazza, McCloskey, & Green, 1981; Clement, 1982; McCloskey, 1983a&b; McCloskey & Kohl, 1983; McCloskey, Washburn, & Felch, 1983; Kaiser, Proffitt, & McCloskey, 1985; Kaiser, Jonides, & Alexander, 1986; Kaiser, McCloskey, & Proffitt, 1986). These studies on dynamical understandings, "Intuitive Physics" (McCloskey, 1983a), have been interpreted as showing that people often hold erroneous beliefs about simple object motions. We propose a somewhat different interpretation for this literature.

Although seemingly unintentional: Almost all intuitive physics studies investigated people's understandings of motions in point particle systems. Even though the objects presented in these studies were extended forms, such as balls rolled through C-shaped tubes, bombs dropped from airplanes, and coins tossed in the air, the relevant dynamics in these events are fully specified by the motion of the objects' centers-of-mass.

We believe that people become muddled on these problems because they misconstrue them as being extended body systems. McCloskey and his colleagues constructed problems that typically presented an extended body system, for example, a pendulum swinging back and forth. Something happens which transforms this system into a particle motion - the pendulum tether breaks - and the participants are asked to predict the ensuing motion. In this problem, the object's dimensionality must be segregated by reasoning across the events pre- and post-tether breaking epochs.

Kaiser and Proffitt (Kaiser, Proffitt, & Anderson, 1985; Kaiser & Proffitt, 1986) investigated most of McCloskey and his colleagues' situations by having people make judgments in paper and pencil contexts, and when viewing animated computer graphics simulations of these events. The previous results were replicated for the paper and pencil problems; however, it was found that <u>when viewing ongoing displays, people view their erroneous predictions as anomalous, and select natural motions as being correct</u>. As was found in the Archimedes' Principle study, animation segregates the dimensionality of these events in time.

Consider the example of the pendulum problem. Most incorrect responses to the paper and pencil problem are found when subjects are asked to predict the trajectory that the bob would take if the tether broke at the instant when the bob was at the apex of its arc. Most erroneous responses predict that the bob will fall along a parabolic path rather than straight down. Now, at the instant that the bob is at its apex, it is stationary. Ask anyone what happens when a stationary object is dropped and they will predict a straight down trajectory. The difficulty that people have with the pendulum question clearly involves their inability to construe the state of the bob's motion at the instant when the tether breaks. When viewing the ongoing event, the object's extended and particle motion contexts - swinging versus falling - are clearly separated in time.

It should be here emphasized that the advantage that ongoing displays have been shown to have in eliciting accurate dynamical intuitions is restricted to situations in which accurate judgments can be based on single object dimensions. For cases in which emergent multidimensional quantities must be formed, for example, when evaluating the dynamics of a spinning top, viewing the ongoing event does not spontaneously result in better dynamical intuitions.

Perceiving Apparent Extended Body Motions.

We investigated apparent motion trajectories for stimuli flashed in different locations and at different orientations (Proffitt, Gilden, Kaiser, & Whelan, 1988). These experiments showed that apparent extended body motions reflect perceptual processes not revealed by studies on perceiving apparent particle motions.

Apparent particle motions involve object displacements without orientation change. They occur when stimuli consist of such non-orientable shapes a points or circles; however, particle motions also occur when orientable shapes undergo displacements without changing their orientation. These motions are particulate since they are reducible to the motions of objects centers-of-mass; object configuration is irrelevant. Apparent extended body motions include orientation changes. They occur whenever an orientable object changes its orientation. Thus, extended body motions involve all of the possible displacements found for particle motions in conjunction with those motions that yield orientation changes. Object configuration is relevant since an object's center-of-mass, being a point-particle, has no orientation specificity. This categorization of apparent object motions depends not on whether objects are particulate or extended, but rather on the motion context in which they are found.

The essence of our experimental situation is depicted in Figure 3. Panel A shows a rectangle alternately flashed at different orientations in different locations. The fact that this event involves an orientation change defines it as being an extended body motion. Panel B and C show two theoretically motivated alternatives for the apparent trajectories that could be seen. The single rotational trajectory depicted in Panel B represents the minimum motion for a kinematic representation of this event (Foster, 1975; Carlton & Shepard, 1988). A kinematic representation treats the situation purely in terms of motions, disregarding dynamical (kinetic) considerations. Panel C shows another alternative in which the rectangle rotates about its centroid as this point moves linearly. This alternative represents a dynamical minimization of energy (assuming that the rectangle has some mass and is otherwise unconstrained with regard to its potential motion paths). Previous to our work, some research support existed for both alternatives.

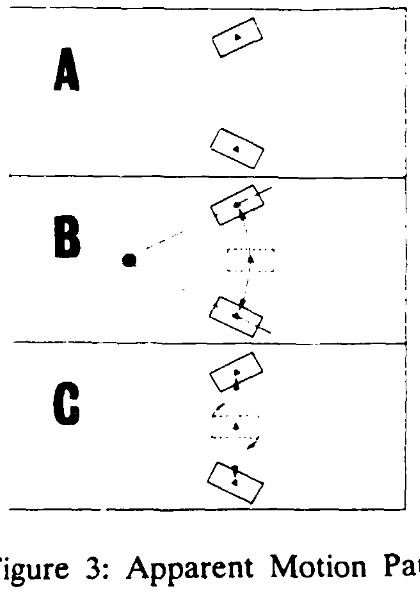

Figure 3: Apparent Motion Paths

It was found that apparent extended body motions followed curved paths; however, these perceived trajectories were actually circular for only a restricted range of parameters. The following variables influenced the extent of curvature seen: (1) The amount of orientation change presented, (2) the orientation of the stimulus relative to its axis of configural symmetry, (3) the salience of configural orientation, and (4) the gender of the observer.

These results incline us toward the view that object motions are represented kinematically (not dynamically). The resulting kinematic variables form the bases for heuristics that structure dynamical intuitions.

Heiko Hecht has completed a Masters Thesis on extended body motions in depth. His results show that Proffitt et al.'s (1988) findings generalize to objects that are perceived to change orientation about an axis that is not normal to the picture plane (i.e. rotations in depth). This work is being prepared for journal submission.

Conclusion

In this technical report we have presented our account of dynamical event complexity, and have related this account research on common sense dynamical understandings. We find that common sense dynamical understandings are good only when people can accurately base their judgments on a single dimension of information present in the event.

Our account of dynamical event complexity begins with a recognition that there exists a definite limit to the simplicity of mechanical systems. By placing all object motions that adhere to this limit within one class of object motions, we define two categories of dynamical events: Particle motions and extended body motions. These two classes of events are distinguished by the number of object properties of dynamical relevance to the motion context. For particle systems, only the motion of the object's center-of-mass is relevant to its dynamics, whereas for extended body systems, mass distribution, orientation, rotation, and other properties are dynamically relevant variables. It is important to keep in mind that the relevance of object properties depends not on the object itself, but on the motion context in which the object is observed.

Dynamical analyses of particle motions are much simpler than are those of extended body motions. This is due to the increased number of variables that must be included in an adequate dynamical representation of extended body events. Particle motions can always be represented by equations that relate only one category of information; position over time. In essence, particle systems can be understood in terms of center-of-mass displacements. Dynamical representations of extended body motions always relate more than one category of information. In extended body motions, it is not sufficient to know where an object's center-of-mass is located, rather such relational properties as mass distribution - how much of the object's mass is located where - must be appreciated. The relating of different categories of information is performed through multiplicative processes and results in multidimensional quantities that are not categories of perception.

The definition of dimensionality that we have provided was obtained from physics, and thus, does not serve to define dimensionality in perception. From the point of view of human performance, there are two questions. The first is what configural and kinematic patterns can be distinguished so as to form clear and identifiable dimensions. The second is which of these perceptual dimensions will be construed to be relevant for dynamical judgments. These questions are far from being resolved. Be this as it may, our account, drawn from a physical analysis of dimensionality, defines definite limits on human performance. It has been shown for a variety of situations that people tend to treat multidimensional problems as being unidimensional ones (Shepard, 1964). Extending this finding to dynamical contexts implies that dynamical intuitions must suffer as the boundary is crossed between particle and extended body motion contexts.

People's common sense understandings are fairly good for particle motions. Although people sometimes make erroneous predictions due to their misrepresenting the dimensionality of these simple systems, their dynamical judgments are quite accurate when they are actually observing the ongoing events. Animation often segregates *event dimensionality in time.*

When people attempt to form dynamical understandings of extended body motions, dynamical competence begins to break down. When asked to predict the behavior of rolling wheels, almost no one anticipates that mass distribution will affect the rate at which a wheel rolls down an inclined plane. Increasing the complexity of object motions to that found in tops and gyroscopes produces a perceptual catastrophe that is experienced as <u>wonder</u>. Perception in such situations informs us that there exist forces that we cannot appreciate. Tops and gyroscopes are wonderful, in part, because in perceiving their apparent gravity-defying behavior, we become aware of our own perceptual limitations.

Gravity is, of course, also wonderful in this sense; it acts as an invisible force. However, the perceived effect of gravity in particle versus extended body motions is profoundly different. Dropping a spinning and a nonspinning top off a tower will produce equivalent falling trajectories that are easily assimilated by common sense. Placing these objects on a pedestal results in quite different motions: The nonspinning top falls down, whereas the spinning top falls sideways, thereby causing it to precess. This latter event cannot be assimilated by common sense.

There are people, physicists, who have a dual awareness of the characteristics of mechanical systems. This awareness schism is quite interesting to observe and is easily elicited. Most of the problems discussed above were presented to a group of 19 high school physics teachers, individuals who, more than any other group, are responsible for explaining the elementary principles of classical mechanics to naive students. These teachers were forced to answer the questions fairly rapidly, thereby prohibiting them from generating the formal representation for each problem that would allow for an analytical derivation of the correct answers. The performance of this group was no better than that found for the tested undergraduates or university physics professors interviewed under similar time constraints.

Prevent a competent physicist from making explicit calculations about such events as rolling wheels and they exhibit the same basic confusions that are found in naive observers; they are generally aware that mass is not relevant since the equivalence principle (that all objects are accelerated at the same rate regardless of mass) is second nature, but they are often not so sure about radius and mass distribution. However, if given time, most physicists could work the problem out in a few minutes. At this point the average physicist will inform you that the rolling wheel problem is trivial. This is the second awareness: The formal understanding of the mechanical system.

It is the goal of physics educators to encourage in their students the development of this second awareness. The intuitive physics literature has been influential in framing theories of what constitutes learning physics. It particular, it has been frequently suggested that physics instruction should take into account the naive believes that students bring to the learning situation (Champagne, et al. 1980, Clements, 1982, McCloskey 1983a; Reif, 1986; Carey, 1986) We believe that this prescription is likely to be misapplied. Our preliminary investigations suggest that: <u>For complex extended body motions, people's dynamical understanding failures are not due to their holding erroneous theories, rather these failures result from intrinsic limitations in processing dynamical information.</u> In the example of the rolling wheel given above, people are more often muddled than misguided. Moreover, physicist and physics teachers share with naive individuals a sense of befuddlement with the extended body motions that we have examined. We propose that the adequacy of common sense dynamical judgments depends on the degree of dimensionality that is both (1) inherent in the physics of the event, and (2) presumed to be present by the observer.

What then constitutes learning physics and what is going on when a physicist spends a quarter of an hour working out a problem and then tells you that it is trivial? We do not propose a theory of learning in this paper, but we do offer the following idea: Learning physics is the transportation of common sense notions of symmetry and simplicity to the mathematics that describe dynamical events. In this sense, learning physics is concerned with a change in the domains of understanding: A shift from the phenomenal world to the formal world captured by the calculus of variations. What makes the rolling wheel problem trivial is that its mathematical structure is very simple; the manifest symmetries between the rotational and translational degrees of freedom are easily displayed in a simple and compact notation. Furthermore, the equation of motion can be solved analytically in terms of elementary functions and integrals. Even if it is not possible to see what is going on with a rolling wheel, it is easy to see what is going on with its mathematics. What is common to common sense and the formalisms of physics are their inherent symmetries, symmetries that form the basis for their intelligibility.

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